Lightning NOx (LNOx)

Joint MTG LI Mission Advisory Group & GOES-R GLM Science Team Workshop

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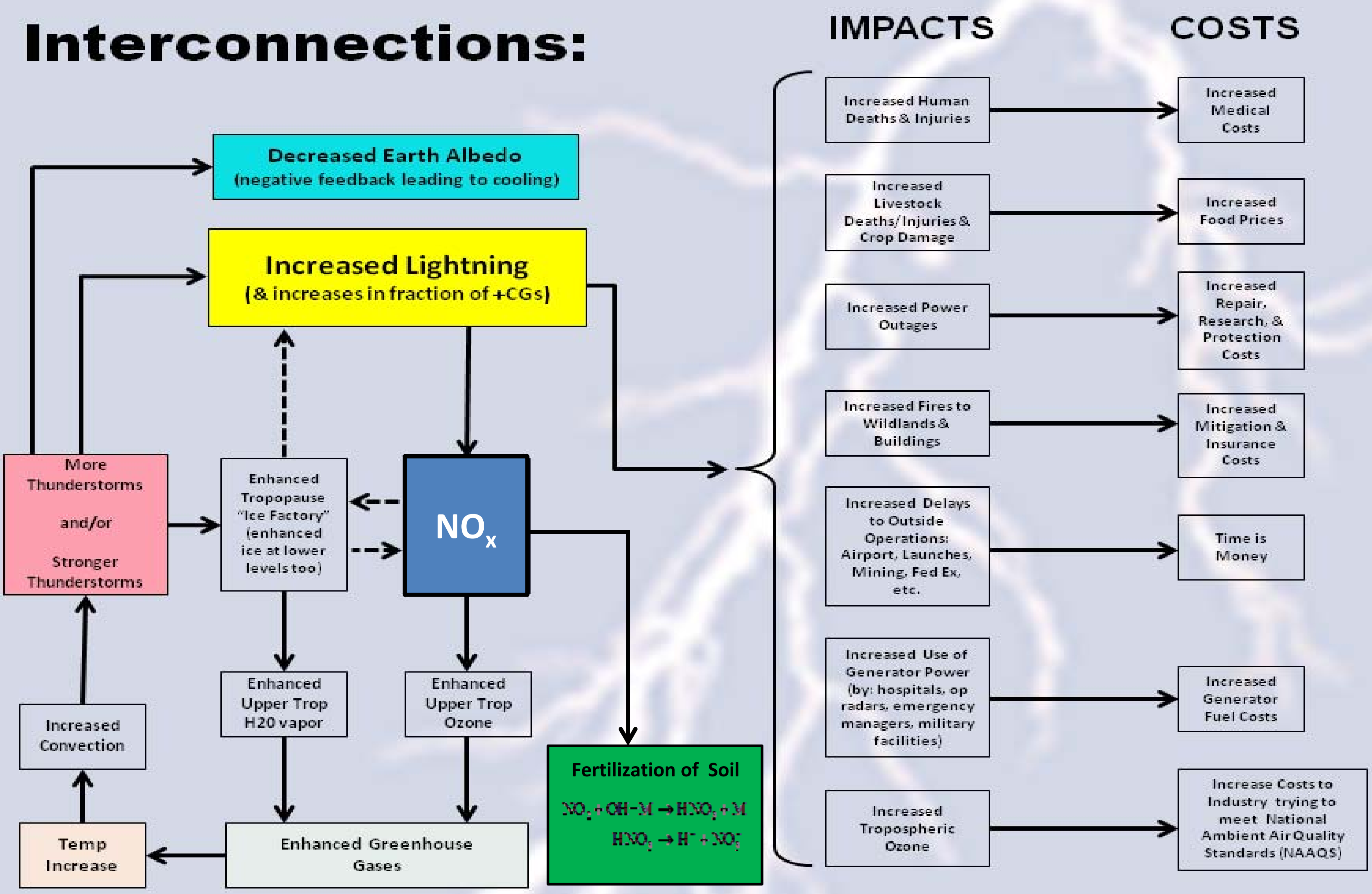
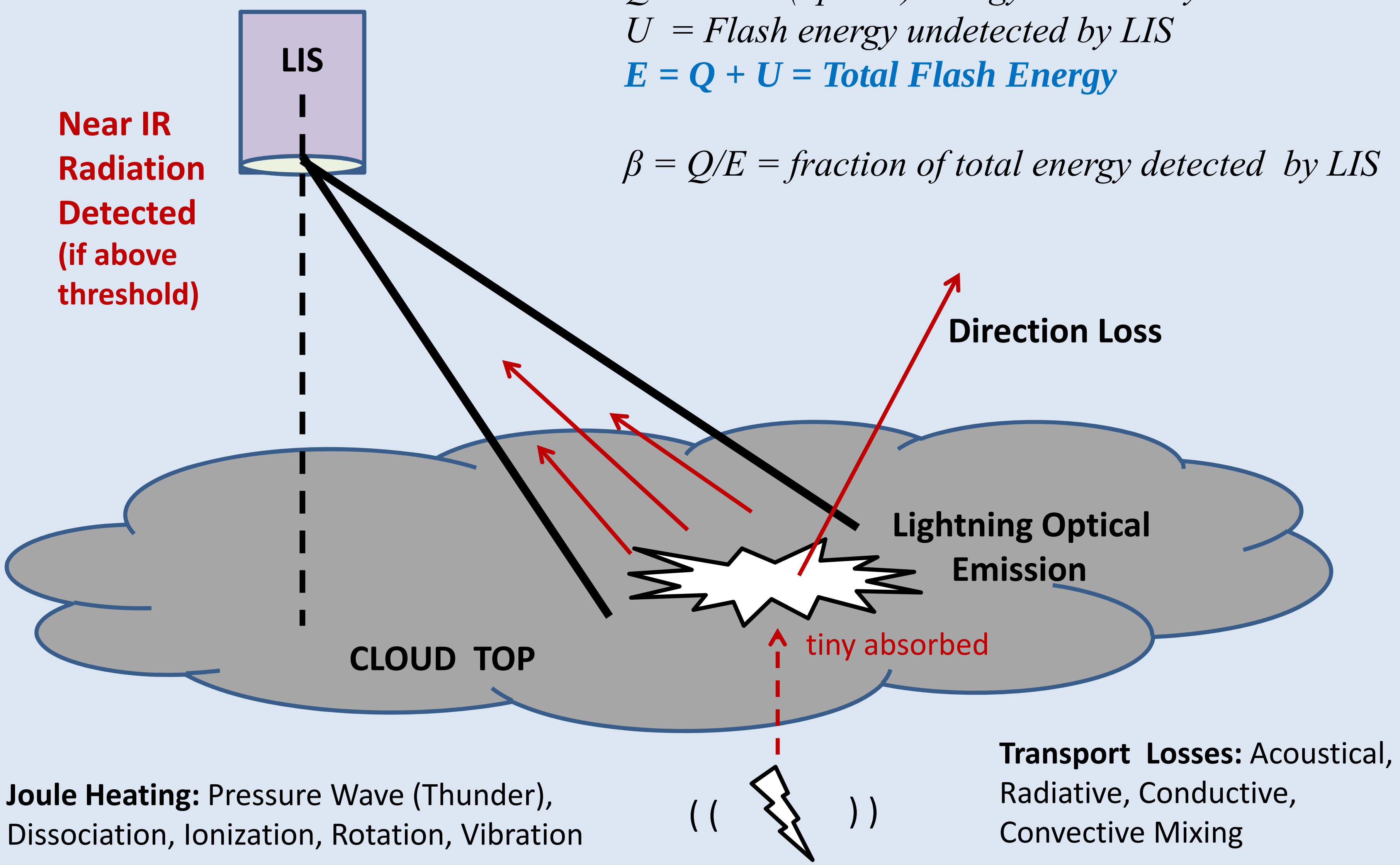
IMPORTANCE OF LNOx



OPTICAL ENERGY INTERCEPTED

Q = Flash (optical) energy detected by LIS
U = Flash energy undetected by LIS
$E = Q + U$ = Total Flash Energy

$\beta = Q/E$ = *fraction of total energy detected by LIS*



LNO_X PRODUCTION FROM ONE FLASH

$$\underset{\text{[moles/flash]}}{\text{LNOx Production}} = \underbrace{\left(\frac{Y}{N_A}\right)}_{\text{[moles/Joule]}} \underbrace{\frac{Q}{\beta}}_{\text{[Joules/flash]}}$$

$\beta = Q/E$ = fraction of total energy detected by LIS

Y = Thermo-chemical Yield = 10^{17} molecules/Joule

N_A = Avogadro's Constant = 6.022×10^{23} molecules/mole

PRODUCTION FROM MANY FLASHES

$$P = \sum_{k=1}^{N} P_k = \left(\frac{Y}{N_A}\right)\sum_{k=1}^{N}\frac{Q_k}{\beta_k}$$

$$\beta_k = \beta_k(\text{instrument, thundercloud, lightning flash})$$

$$P \cong \left(\frac{Y}{\beta^* N_A}\right)\sum_{k=1}^{N} Q_k = K\sum_{k=1}^{N} Q_k$$

$\beta^* = 1.8675 \times 10^{-19}$ = The value required such that the mean production from the 73,292 flashes observed by LIS over CONUS in the year 1998 (arbitrary reference year) is **250 moles / flash**.

$K = 8.8920 \times 10^{11}$ moles/Joule

FUNDAMENTAL QUESTION

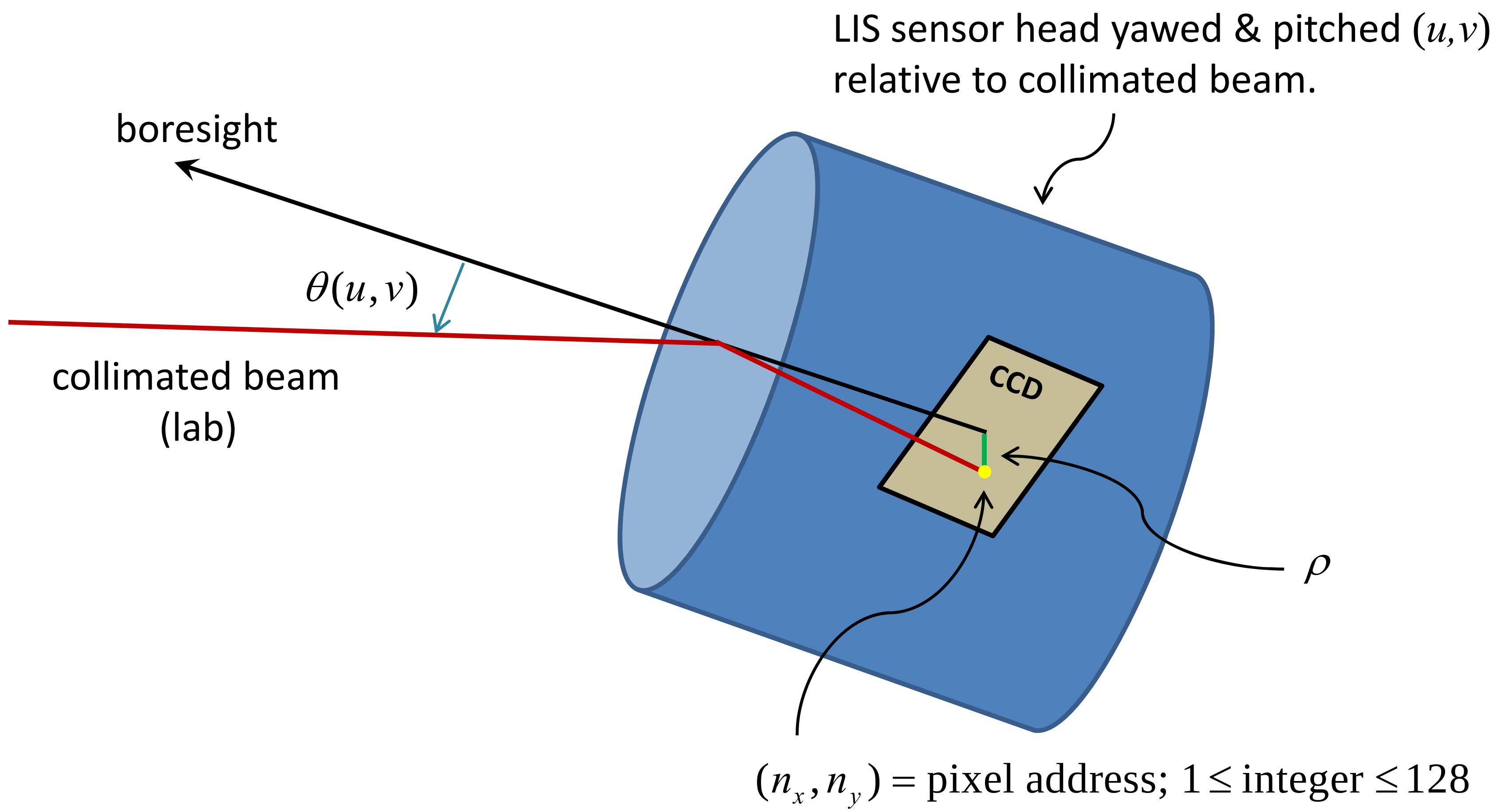
How does one compute the optical energy Q_k detected from the LIS science data?

$$P \cong K \sum_{k=1}^{N} Q_k$$

LIS data provides:

radiance
footprint
location
time stamp
pixel address
.
.

YAW & PITCH IN CALIBRATION LAB



BORESIGHT ANGLE OF AN EVENT

(n_x, n_y) = pixel address; $1 \le$ integer ≤ 128

$x = (n_x - 65)60 + 30$ = pixel x-location (μm)

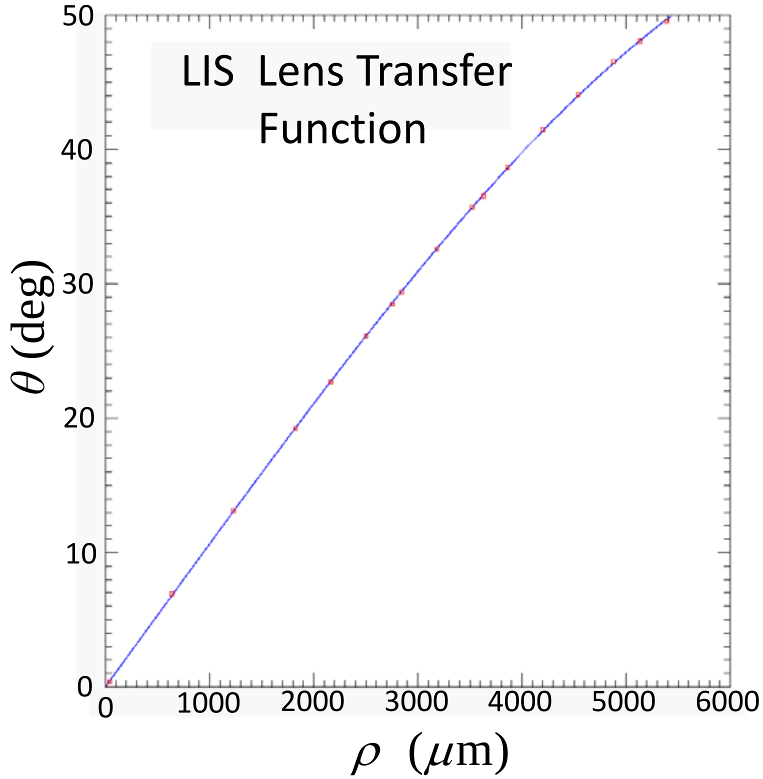
$y = (65 - n_y)60 - 30$ = pixel y-location (μm)

$\rho = \sqrt{x^2 + y^2}$ = pixel distance from center of CCD

$u = u(n_x, n_y)$ = **yaw** of LIS sensor head in cal lab

$v = v(n_x, n_y)$ = **pitch** of LIS sensor head in cal lab

$\theta = \cos^{-1}[-\sin v_o \cos u \sin v - \sin u_o \cos v_o \sin u + \cos u_o \cos v_o \cos u \cos v]$

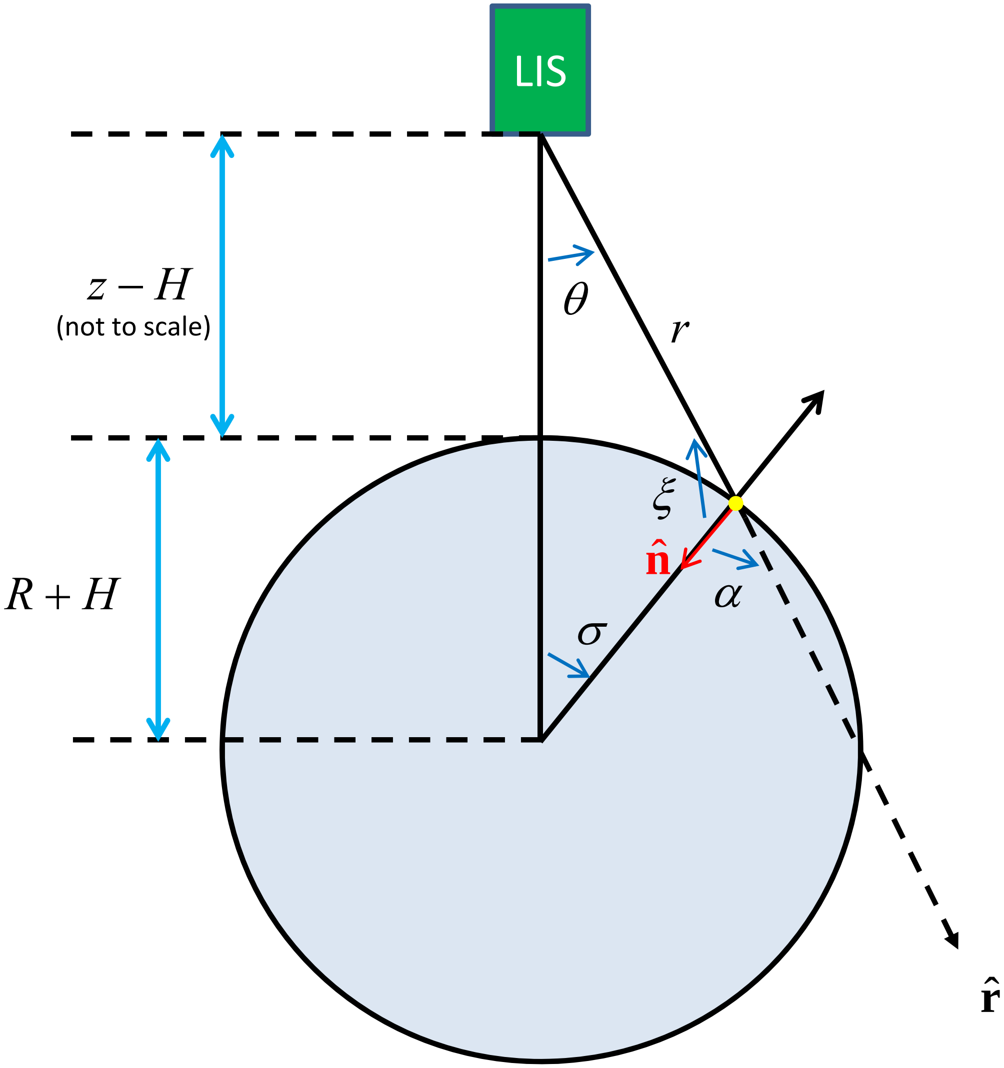


Splining the calibration data gives:

$\theta = \theta(\rho(n_x, n_y)) = b_3\rho^3 + b_2\rho^2 + b_1\rho + b_o$ = boresight angle of illuminated pixel

That is: $(n_x, n_y) \to \rho \to \theta$

SOLID ANGLE OF AN EVENT



R = Earth radius

H = cloud-top height

z = orbital altitude

a = event footprint (area)

$$\Delta\omega \approx \frac{a\cos\alpha}{r^2} = \text{solid angle of event}$$

where Law of Sines & geometry gives:

$$\alpha = \sin^{-1}\left[\left(\frac{R+z}{R+H}\right)\sin\theta\right] = \text{foreshortening angle}$$

$$r = (R+H)\frac{\sin(\alpha-\theta)}{\sin\theta} = \text{range}$$

FLASH OPTICAL ENERGY DETECTED

$$Q_k = CA\Delta\lambda \sum_{i=1}^{m_k} \sum_{j=1}^{n_k} \left[\frac{a_{jk} \cos \alpha_{jk}}{r_{jk}^2} \right] \bar{\xi}_{\lambda ijk} = \text{ LIS-detected optical energy of kth flash}$$

a_{jk} = event footprint (j^{th} event in the k^{th} flash)

θ_{jk} = event boresight angle

$\bar{\xi}_{\lambda ijk}$ = event energy density

m_k = # frames occupied by kth flash

n_k = # pixels illuminated by kth flash.

z = LIS orbital altitude

A = LIS entrance aperture area

$\Delta\lambda$ = LIS bandwidth

R = Earth Radius

C = conversion factor

$$r_{jk} = (R + H)\frac{\sin(\alpha_{jk} - \theta_{jk})}{\sin\theta_{jk}} = \text{range (from event footprint to LIS)}$$

$$\alpha_{jk} = \sin^{-1}\left[\left(\frac{R + z}{R + H}\right)\sin\theta_{jk}\right] = \text{foreshortening angle}$$

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PRODUCTION (FINAL ESTIMATE)

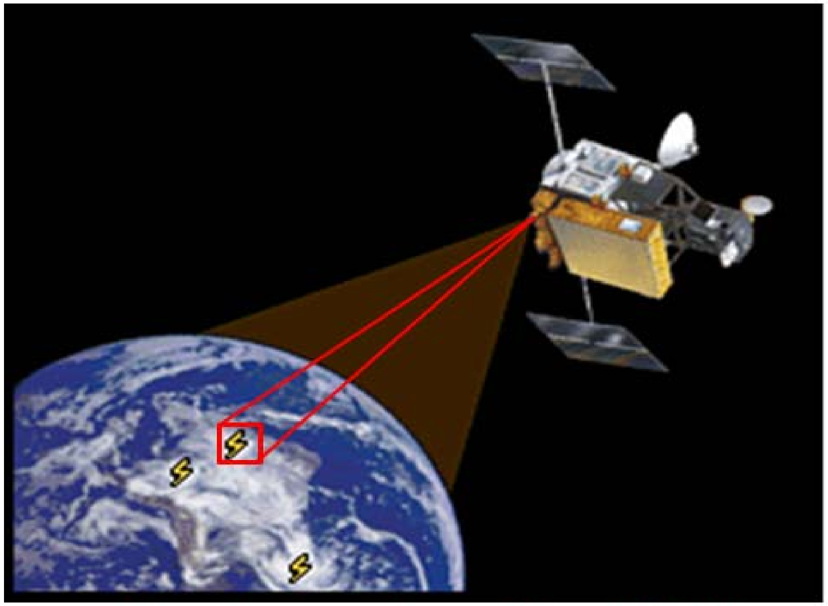
Boost Number of Flashes based on:

- LIS Detection Efficiency
- LIS Viewtime

So have:

$N_o =$ Number observed

$N_t =$ Total Number Estimated



LIS shown detecting optical energy Q_k from the k^{th} flash.

$$P_t \cong K\sum_{k=1}^{N_o} Q_k + \underbrace{(N_t - N_o)}_{\text{Boost}} \underbrace{\left(K \frac{1}{N_o} \sum_{k=1}^{N_o} Q_k \right)}_{\text{Ave Prod per flash}}$$

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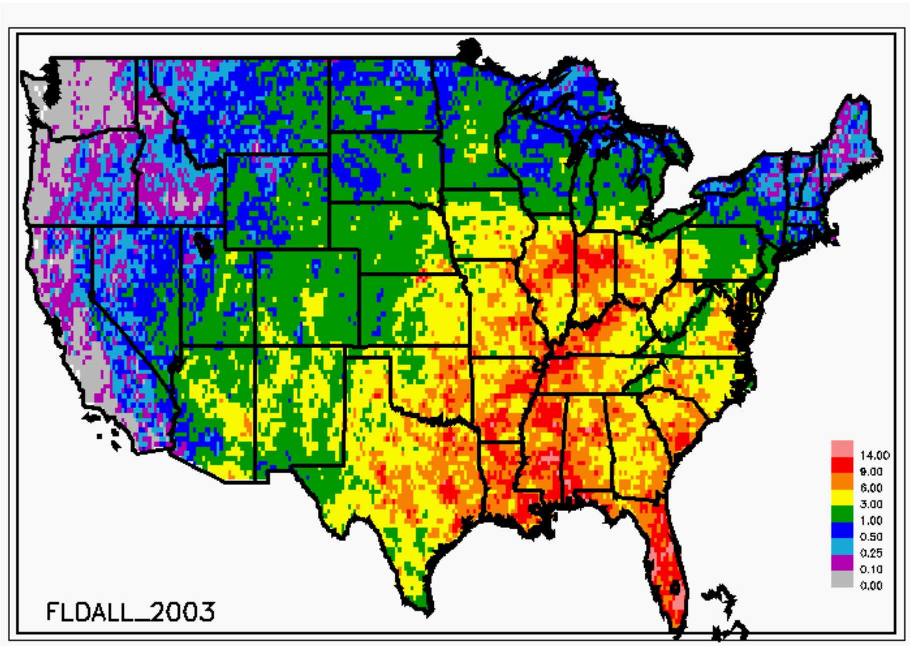
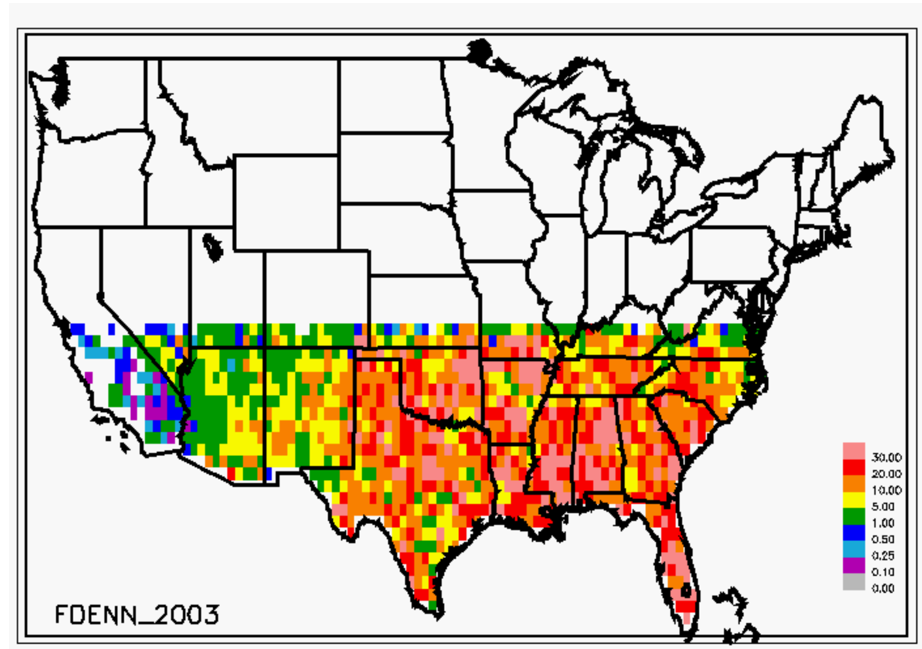
NLDN Flash Density (2003-2012)



LIS Flash Density (2003-2012)



Compared CGs to total lightning from LIS

Year	NLDN	LIS (Raw)	LIS (DE & VT Corrected)
2003	25,312,151	100,090	50,435,202
2004	26,515,549	100,695	51,831,376
2005	25,733,836	96,522	47,837,176
2006	25,110,025	78,787	40,511,787
2007	23,350,168	87,181	44,373,486
2008	22,888,321	90,307	44,772,072
2009	22,233,574	95,793	48,724,951
2010	22,793,791	93,751	49,250,190
2011	23,825,025	96,680	48,989,029
2012	18,192,183	86,766	44,139,720

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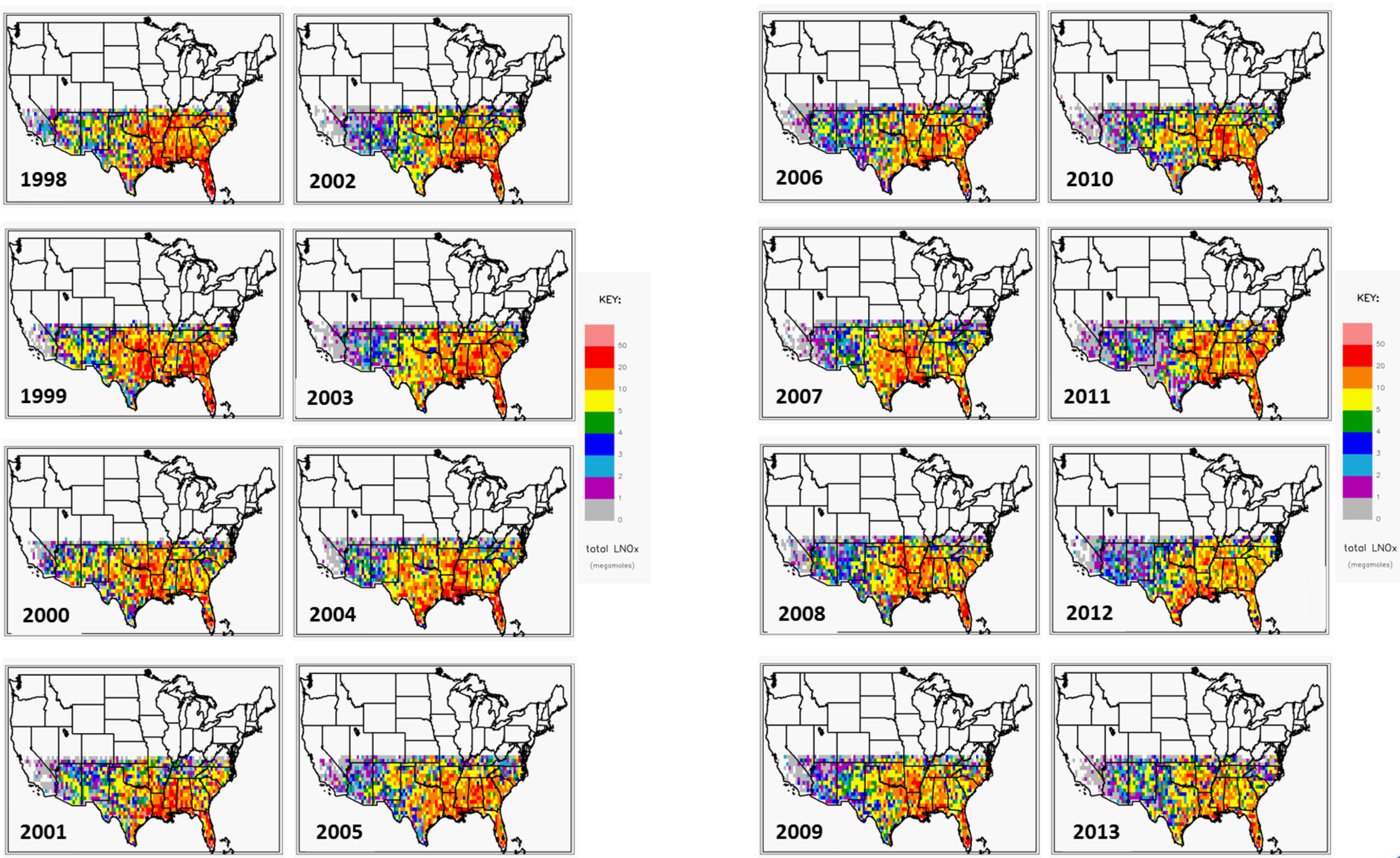
1998-2013 LIS-INFERRED LNOx (megamoles)



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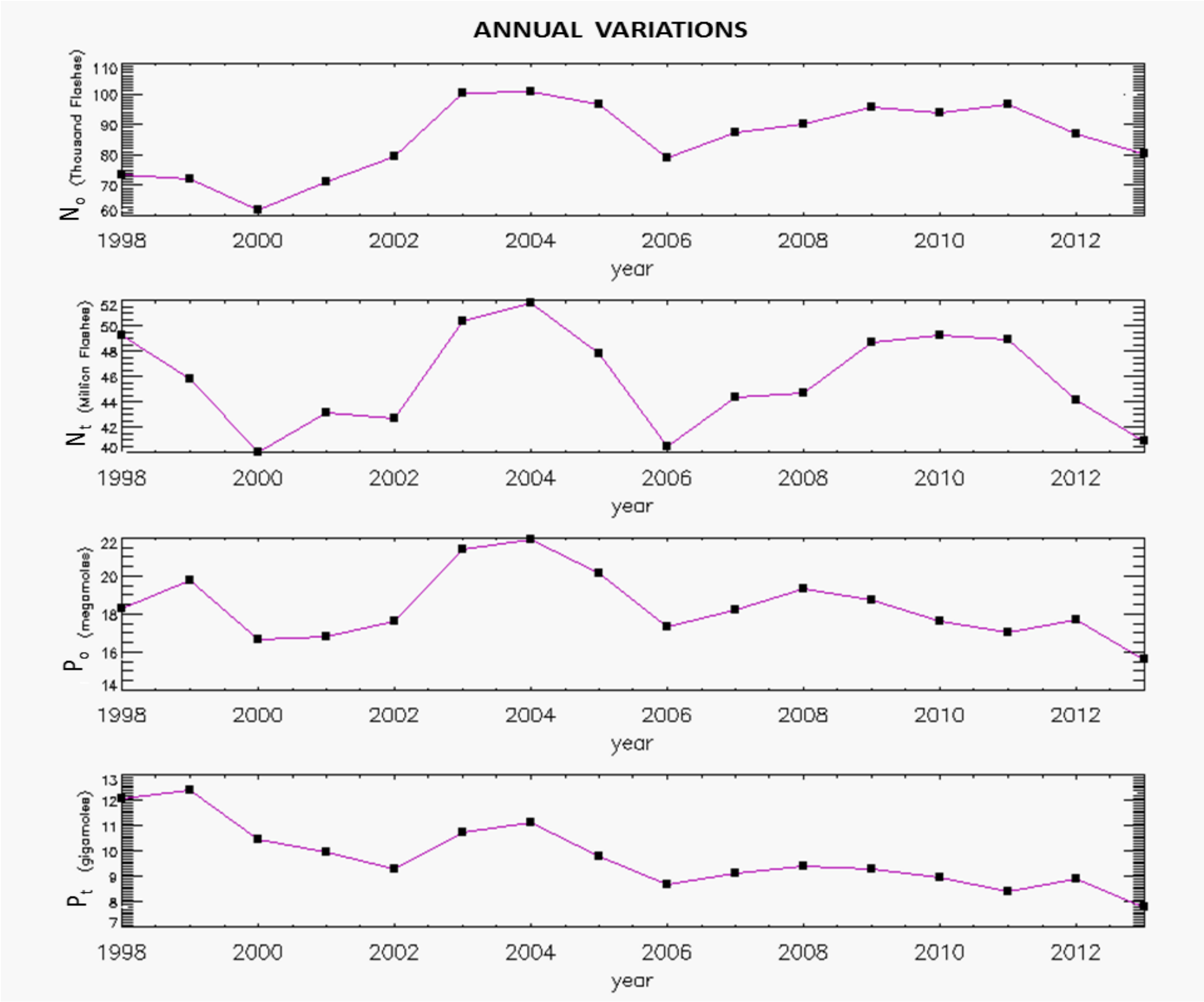
FLASH COUNT & LNOx TIME SERIES (1998-2013)



~ 33% drop in LNOx

Main Result

USER COMMUNITY & DECISION MAKERS

- **Chattanooga Hamilton County Air Pollution Bureau**
  - Address: 6125 Preservation Dr, Chattanooga, TN 37416.
  - Monitors Air Quality, and proceeds with enforcement actions if air quality violations are determined.
- **Point-Of-Contact**
  - Kathy Jones – Air Monitoring Manager.
  - She would like to know better to what extent ozone exceedances are attributable to lightning.

Sample of Jone's estimates of lightning-caused exceedances … but desire is to improve accuracy of these analyses.

OZONE	Exceedance of 75 STD 8-Hour		Association with Significant Lightning
2012			
June 28-July 1	Yes		Yes
2011			
June 7, 8	Yes		No
August 17,18	Yes		No
September 2	Yes		No
2010			
May 5,6	Yes		No
April 2	No	Day before	Yes
April 13,14	Yes		Yes for 4/14
August 4	Yes		Yes
August 10,11	Yes		Yes
September 15	Yes		No
2009			
March 22,23	No		No
April 9	No		Yes for 4/10
June 1,2	Yes		Yes
August 7	No		Yes
June 25, 26	No		Yes
2008			
June 25	Yes		No- West of Chatt
July 18,19	Yes		No-West of Chatt
August 4	Yes	Day Before	Some
August 19	Yes	Day Before	Some

BENEFITS OF SIMILAR STUDIES USING GLM

- **Events Already Given In Terms of Joules**
- **Continuous 24/7 Monitoring Helps:**
  - Better assess β_k
  - Better support of LNOx-caused ozone exceedances
  - Provides unprecedented LNOx Emission Inventory for CMAQ, thus improving ozone air quality forecasting

Thank You